WESTINGHOUSE SOLID-ELECTROLYTE FUEL CELL

Fuel Design Group

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The basic component of the Westinghouse solid-electrolyte fuel cell is the $(ZrO_2)_{0.85}\ (CaO)_{0.15}$ [or $(ZrO_2)_{0.9}\ (Y_2O_3)_{0.1}$] electrolyte. This material is an impervious ceramic which has the unique ability to conduct a current by the passage of $O^=$ ions through the crystal lattice. The ease with which these ions pass through the electrolyte is measured by the electrical resistivity, ρ_b, of the electrolyte. Values of ρ_b for both $(ZrO_2)_{0.85}\ (CaO)_{0.15}$ and $(ZrO_2)_{0.9}\ (Y_2O_3)_{0.1}$ as functions of temperature, T, are given in Figure 1. The resistance of a disc of $(ZrO_2)_{0.85}\ (CaO)_{0.15}$ 2 in. in diameter and 15 mils thick is about 0.1 ohm at 1000°C.

FABRICATING THE CELL

To fabricate a cell from such a disc, porous platinum electrodes are applied to both sides. On the lower electrode of Figure 2 a molecule of O_2 gas from the surroundings acquires 4 electrons and forms 2 $O^=$ ions, which enter the crystal lattice of the ceramic. At the upper electrode, 2 $O^=$ ions emerge from the electrolyte, give up 4 electrons, and recombine to form O_2. The lower electrode is positively charged; the upper is negatively charged if O_2 flows upward through the electrolyte.

The most direct method for bringing about this flow is to construct one chamber around the lower electrode in which O_2 is kept at a high partial pressure and another chamber around the upper electrode in which the partial pressure of O_2 is maintained at a low value. In this case, the observed open circuit voltage of the cell, E_t, can be computed from

$$E_t\ (4\,\mathcal{F}) = RT \ln \left(P_{O_2,H} / P_{O_2,L}\right) \qquad (1)$$

where $4\mathcal{F}$ = 4 (the Faraday number) = quantity of charge transferred per mol of O_2 passing through the electrolyte, 386,000 coulombs/mol

R = universal gas constant, 8.134 watt-sec/°K mol

T = absolute temperature of cell, °K

$P_{O_2,H}; P_{O_2,L}$ = O_2 partial pressures in lower and upper chambers

$RT \ln (P_{O_2,H} / P_{O_2,L})$ = work per mol obtained from reversible, isothermal expansion of a gas at temperature T, watt-sec/mol

UTILIZATION AS FUEL CELL

The device can be utilized as a fuel cell by flowing oxygen or air to the lower chamber. If atmospheric air is used, the O_2 partial pressure in the lower chamber is maintained at about 0.2 atm. Fuel flows through the upper chamber, combines with any O_2 present, and reduces the O_2 partial pressure in the fuel chamber to about 10^{-16} atm. (The total pressure in both chambers is 1.0 atm.) The calculated value of E_t in this instance is approximately 1.0 volt.

When a current, I, is drawn from the terminals, the voltage V of the cell drops below the open circuit voltage E_t because of resistance losses in the electrolyte and electrodes.

$$V = E_t - IR \tag{2}$$

where E_t is the voltage computed from Equation 1 and R is the ohmic resistance of electrodes and electrolyte. An approximate expression for the resistance R of a cell is

$$R = \rho_b \, \delta_b / A_b + (\rho_e / \delta_e) \, (L_e / P_e) \tag{3}$$

where δ_b = electrolyte thickness

A_b = active cell area

ρ_e / δ_e = resistivity-thickness quotient for the cell electrodes (See Figure 3)

L_e = mean distance travelled by the electronic current in the electrodes passing from the plus to the minus terminal of the cell

P_e = mean width of the electrode perpendicular to the direction of electronic current flow

For a cell operating at 1000°C using a $(ZrO_2)_{0.85} \, (CaO)_{0.15}$ electrolyte 5 cm in diameter and 0.04 cm thick,

$$R \cong \frac{(60 \, \Omega\text{-cm}) \, (0.04 \text{ cm})}{(\pi/4) \, (5 \text{ cm})^2} + (0.44 \text{ ohm}) \, \frac{(2.5 \text{ cm})}{2\pi) \, (2.5 \text{ cm})}$$

$$\cong 0.12 + 0.07 = 0.19 \text{ ohm}$$

If the electrodes of the cell are sufficiently porous, the IR loss -- as indicated in Equation 2 -- is the only voltage loss in the cell; there are no appreciable voltage drops in the solid-electrolyte cell attributable to the slowness of diffusion or chemical reaction.

CHARACTERISTICS OF SINGLE CELLS

A number of single cells based on these principles have been constructed and tested. The components of a disc cell with an effective diameter of 1.3 inches are shown in Figure 4 and the performance of such a cell is shown in Figure 5. The open circuit voltage of the cell with H_2 fuel is 1.15 volts; its resistance is about 0.4 ohm. The maximum power delivered by the device is 0.85 watt, and the current density at these conditions is 150 amp/ft^2.

SOLID-ELECTROLYTE FUEL CELL BATTERIES

Solid-electrolyte fuel cell batteries have been investigated. One type of battery is constructed of short, cylindrical electrolyte segments shaped so that they can be fitted one into the other and connected into a long tube by bell-and spigot joints. Figure 6 shows an electrolyte segment. A mathematical analysis has been carried out to determine the active cell length L which maximizes the power per unit of cell volume for given values of (1) $\rho_b \delta_b$, the electrolyte resistivity-thickness product; (2) ρ_e/δ_e, the electrode resistivity-thickness quotient (see Figure 3); (3) ℓ , the seal length; and (4) R_{eo}, the electrical resistance of the metal alloy joint which both makes the seal and connects the individual cell segments electrically in series.

An optimized three-cell battery with bell-and-spigot joints is shown in Figure 7. One of the platinum wires at each end of the cell stack is the current lead to the battery; the other wires are probes for measuring potentials throughout the battery.

PERFORMANCE OF BATTERY ON H_2 FUEL AND AIR

The performance of the battery on H_2 fuel and air is shown in Figure 8. The open circuit voltage of the device is below the expected 3.3 volts because of some shorting of the cells occurring in the seal region. Such shorting has been determined to draw about 100 ma in each cell; improved seal design will minimize this loss. In spite of this problem, a current density greater than 450 ma/cm^2 has been achieved in this battery at the maximum power point -- about 1.2 volts. Three of the four joints required in the fabrication of the battery of Figure 8 have been demonstrated to be tight with a helium leak detector. The oxygen leak rate through the fourth joint was shown to be less than the oxygen added to the fuel by a current flow of 20 ma.

PERFORMANCE OF BATTERY ON H_2 FUEL AND PURE O_2

The performance of this same three-cell battery with H_2 fuel and pure O_2 is shown in Figure 9. The open circuit voltage is 2.9 volts. The current density at maximum power was 750 ma/cm^2. At the maximum power point, the battery produces 2.1 watts; and each cell segment, 0.7 watt -- about the same as an ordinary flashlight battery.

The segmented-tube bell and spigot battery gives promise of providing a compact, lightweight power system.

CELL SEGMENT CHARACTERISTICS

The characteristics of the cell segments which make up this battery are given below.

Over-all length, $(L + \ell) = 0.58 + 0.53 = 1.11$ cm
Mean diameter, $D = 1.07$ cm
Electrolyte material: $(ZrO_2)_{0.9}\ (Y_2O_3)_{0.1}$
Electrolyte resistivity-thickness parameter at $1000^\circ C$,
$\rho_b \delta_b = 0.4$ ohm-cm^2
Electrode material: porous platinum
Electrode resistivity/thickness at $1000^\circ C$ $(\rho_e/\delta_e) =$
0.43 ohm-cm/cm
Segment weight (including one joint) = 1.97 gm
Segment volume (including one joint) = 2.0 cm^3

The electrodes of the cell are quite light, and the total weight of the cell is also small -- about 2.0 gm. If the cells are operated at maximum power, the power produced is equivalent to 160 watts/lb of electrolyte and electrodes. (This figure does not include battery casing, insulation, and auxiliaries.) The power per unit volume of the cell unit is 9.5 kw/ft^3.

These performance figures can still be improved by (1) the development of electrodes with lower ρ_e/δ_e values, (2) the use of electrolyte materials with lower ρ_b values, and (3) optimization of the seal dimensions. More power/volume can also be obtained by using smaller diameter cells.

SOLID-ELECTROLYTE FUEL CELL SYSTEMS FOR SPACE

In order to provide a useful power source it is necessary not only to combine the unit cells into batteries but also to provide manifolding, casing, and insulation. All these components must be integrated into a system. A series of 500 watt solid-electrolyte fuel cell systems have been designed for use in space. Stacks of cells connected by bell-and-spigot joints are contained in an insulated cylindrical can which is maintained at the 1027°C operating temperature by the heat generated in operating the system at the design power. The H_2 fuel flows inside each each tube stack and the O_2 oxidant fills the can housing the stacks (see Figure 10). The gas stream emerging from the stacks is water vapor with 4 mole % or less unburned H_2; this gas is exhausted to the surroundings.

Minimum-weight 500-watt systems have been determined for 10-hour, 100-hour and 1000-hour total mission lengths using 1-inch diameter stacks. A choice of 1/2-inch diameter stacks would have resulted in a smaller, lighter device. For a 100-hour mission, the estimated weight of the fuel-cell system (including the cell battery, casing, manifolding, insulation, radiator, and controls) is 25 pounds; the estimated weight of H_2 and O_2 reactants and reactant storage system is 115 pounds. For the 1000-hour mission,the estimated minimum fuel cell system weight is 47 pounds; the reactant and reactant storage weight is 643 pounds.

ADVANTAGES OF SOLID-ELECTROLYTE FUEL CELLS

Although particular solid electrolyte fuel cell systems have been considered, modifications can be made to meet other specific requirements. In addition to their light weight, solid-electrolyte fuel cell systems have distinct advantages over other fuel cells: They are compact; Their high operating temperature enables the heat generated in operating the cell to be radiated to the surroundings without weighty, complex cooling systems and radiators; The electrolyte is physically and chemically stable; There is no difficulty in removing water from the cell (it flows from the system in vapor form); The system operates independently of gravitational forces.

For all these reasons, the solid-electrolyte fuel cell system is a promising candidate for generating power in space.

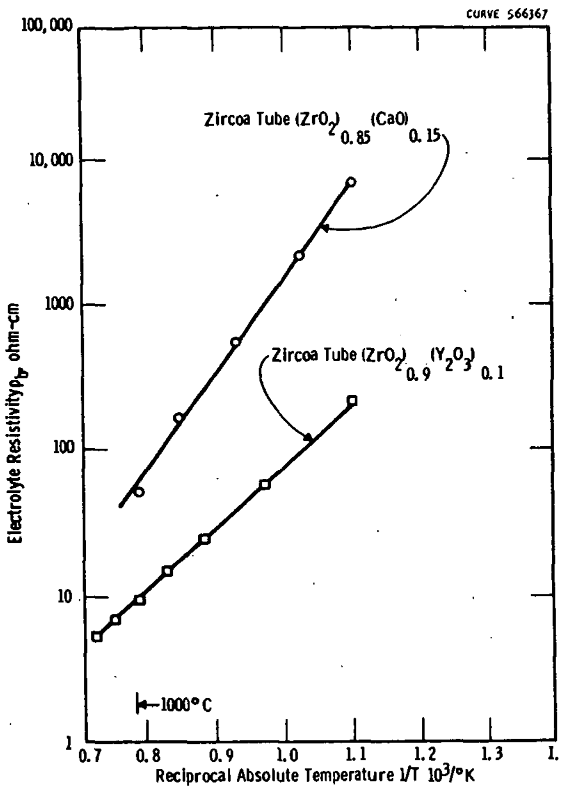
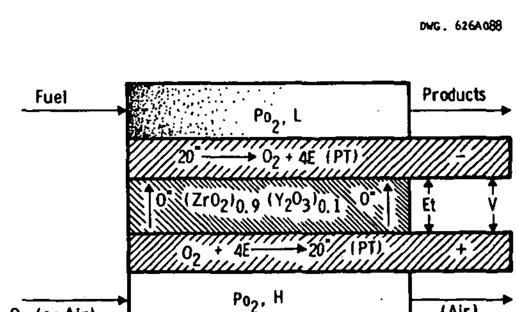


Fig. 1—Electrolyte resistivity-temperature characteristics (CaO and Y_2O_3 stabilized ZrO_2)



$$E_t = \frac{RT}{4F} \ln \left(\frac{Po_2, H}{Po_2, L} \right)$$

$$V = E_t - IR$$

Fig. 2—Solid-electrolyte fuel cell

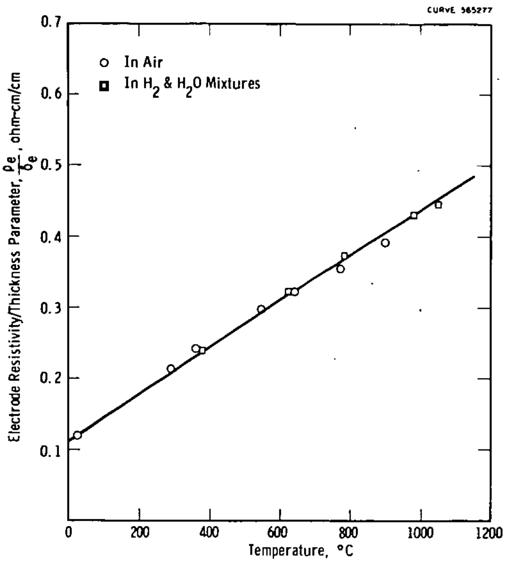


Fig. 3—Characteristics of air-sprayed platinum electrodes

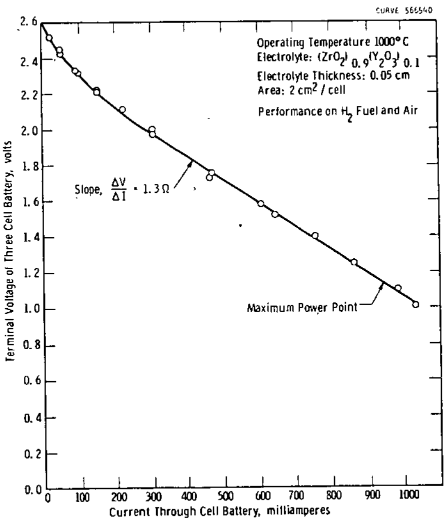


Fig. 8—Voltage-current characteristics of three-cell segmented tube battery with bell-and-spigot joints (H_2 fuel and air)

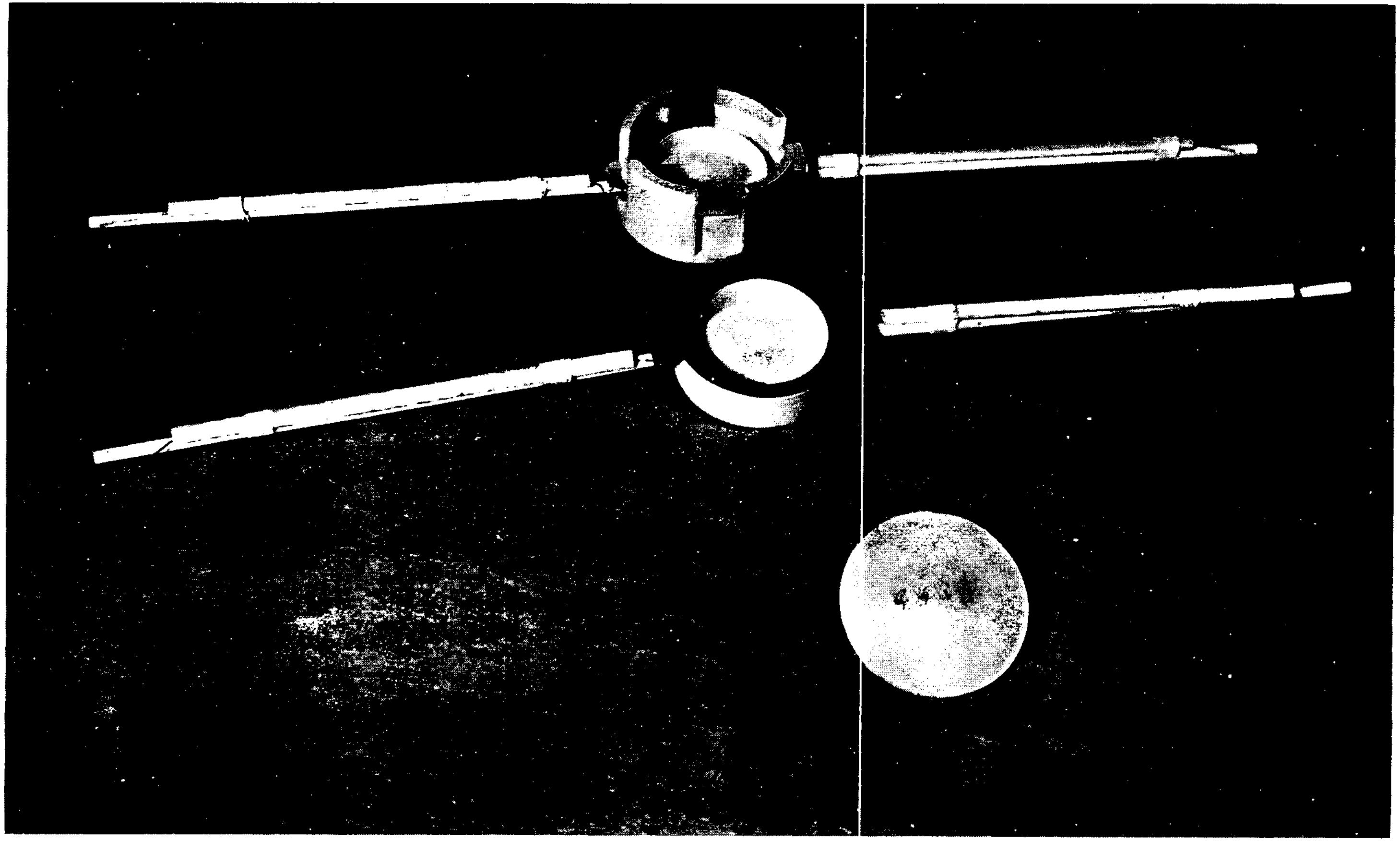


Figure 4. Single Cell Test Assembly

CURVE 523295

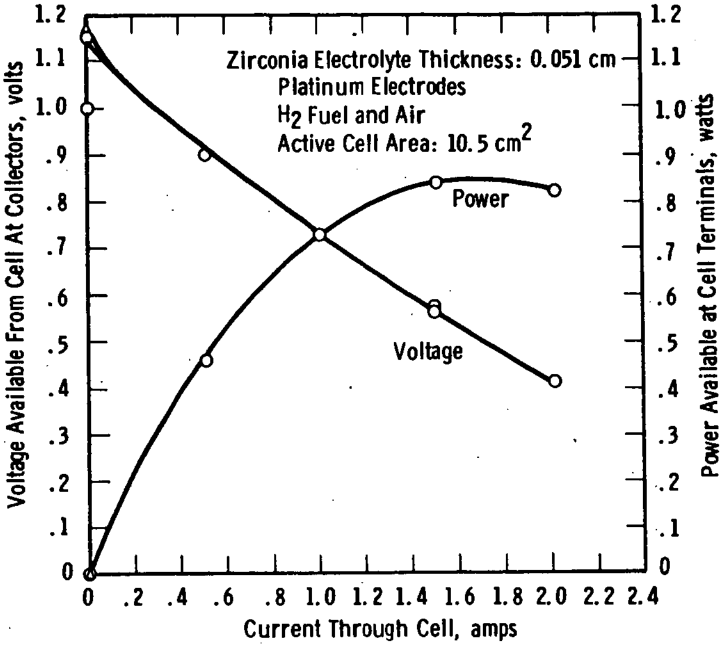


Fig. 5—Voltage and power output of Westinghouse solid-electrolyte fuel cell

DWG. 626A086

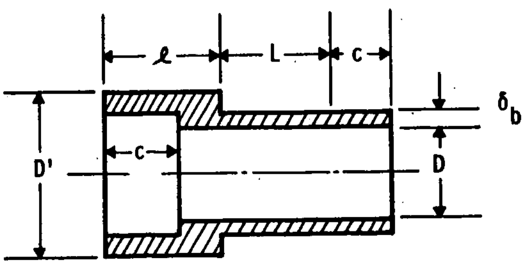


Fig. 6—Cross section of basic cell unit for bell-and-spigot design

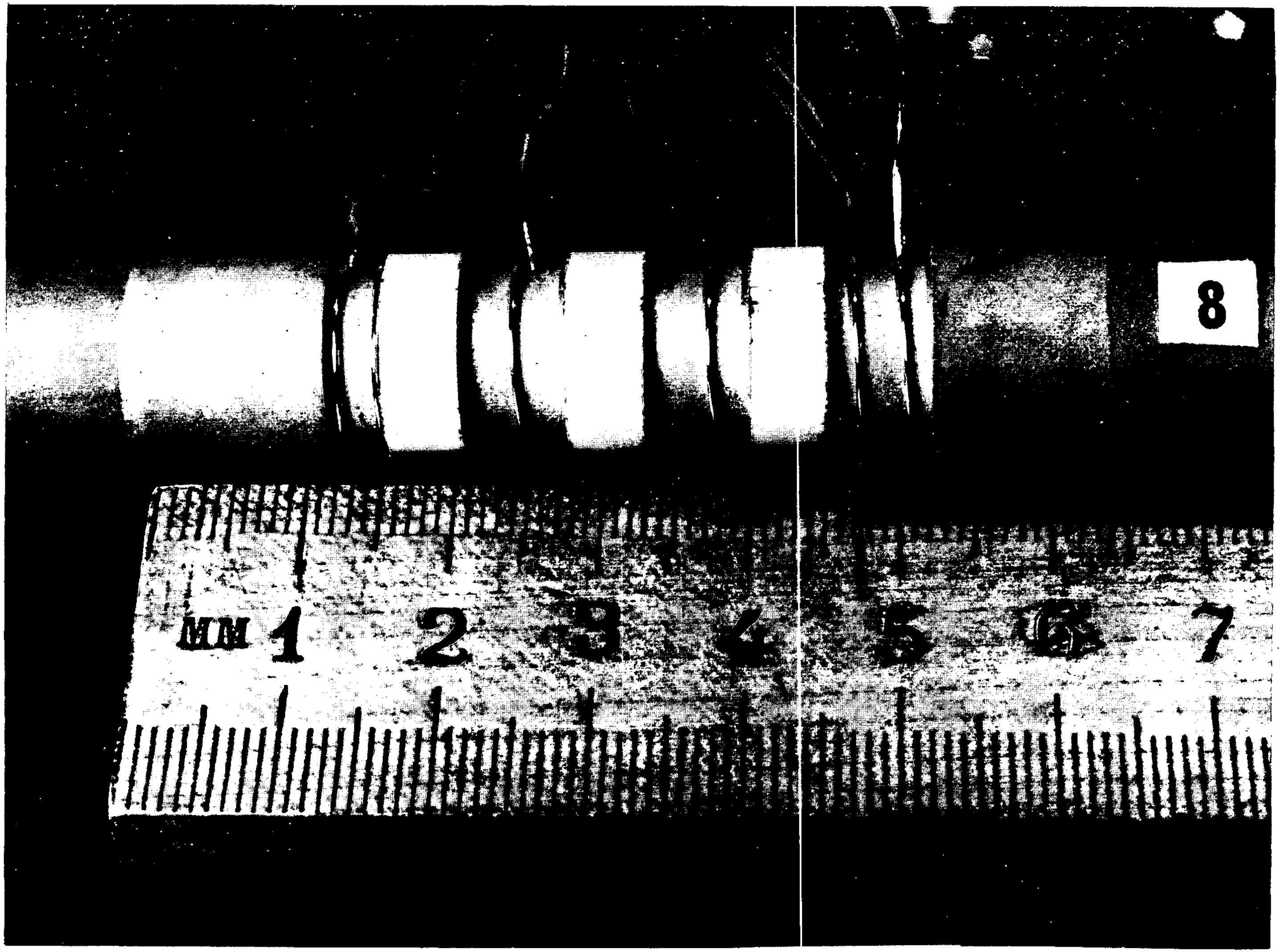


Figure 7. Three-cell segmented tube battery with bell-and-spigot design.

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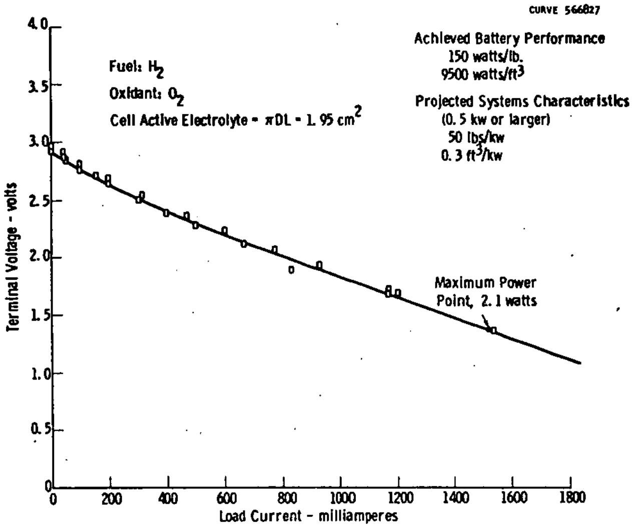

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Fig. 9—Voltage-current characteristics of three-cell segmented tube battery with bell-and-spigot joints (H_2 fuel and O_2)

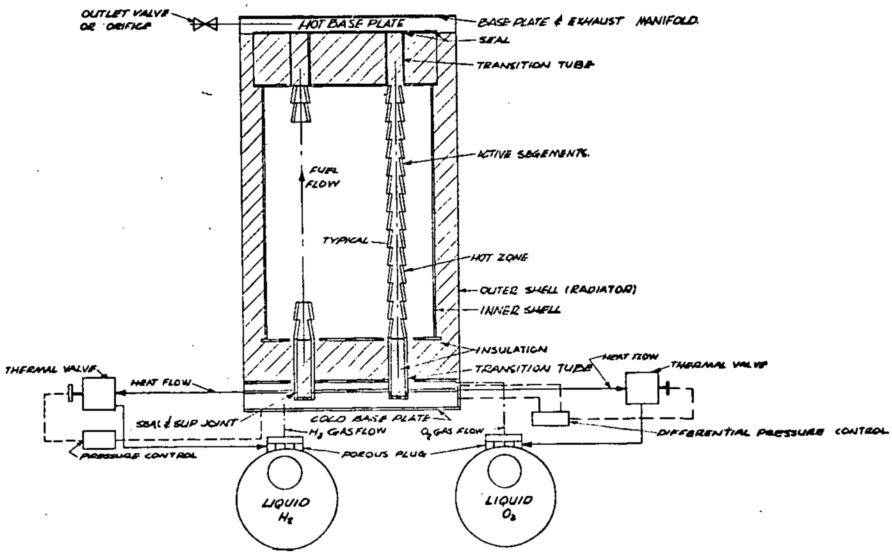

Fig. 10—Diagram of over-all fuel cell system